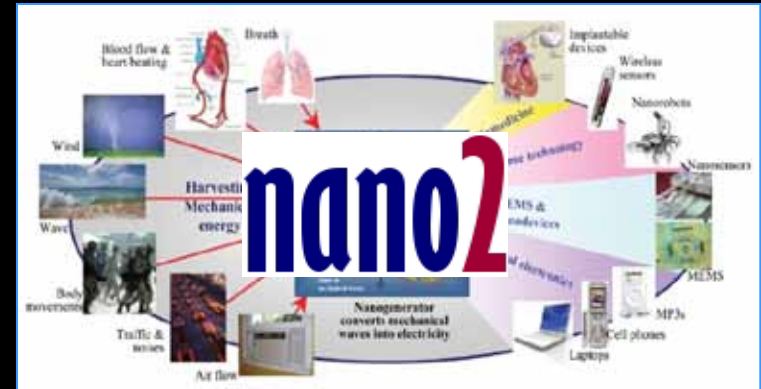


2000



2010



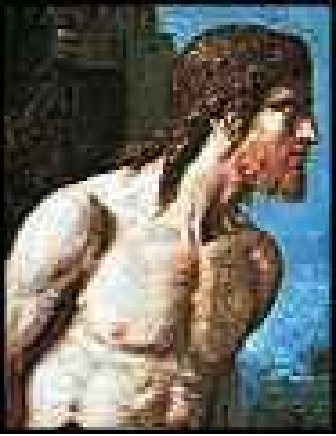
2020

Nanotechnology from Discovery to Socio-economic Projects: 2000-2020

Mike Roco

National Science Foundation and National Nanotechnology Initiative

Nanomanufacturing Summit 2011, Boston, September 27, 2011



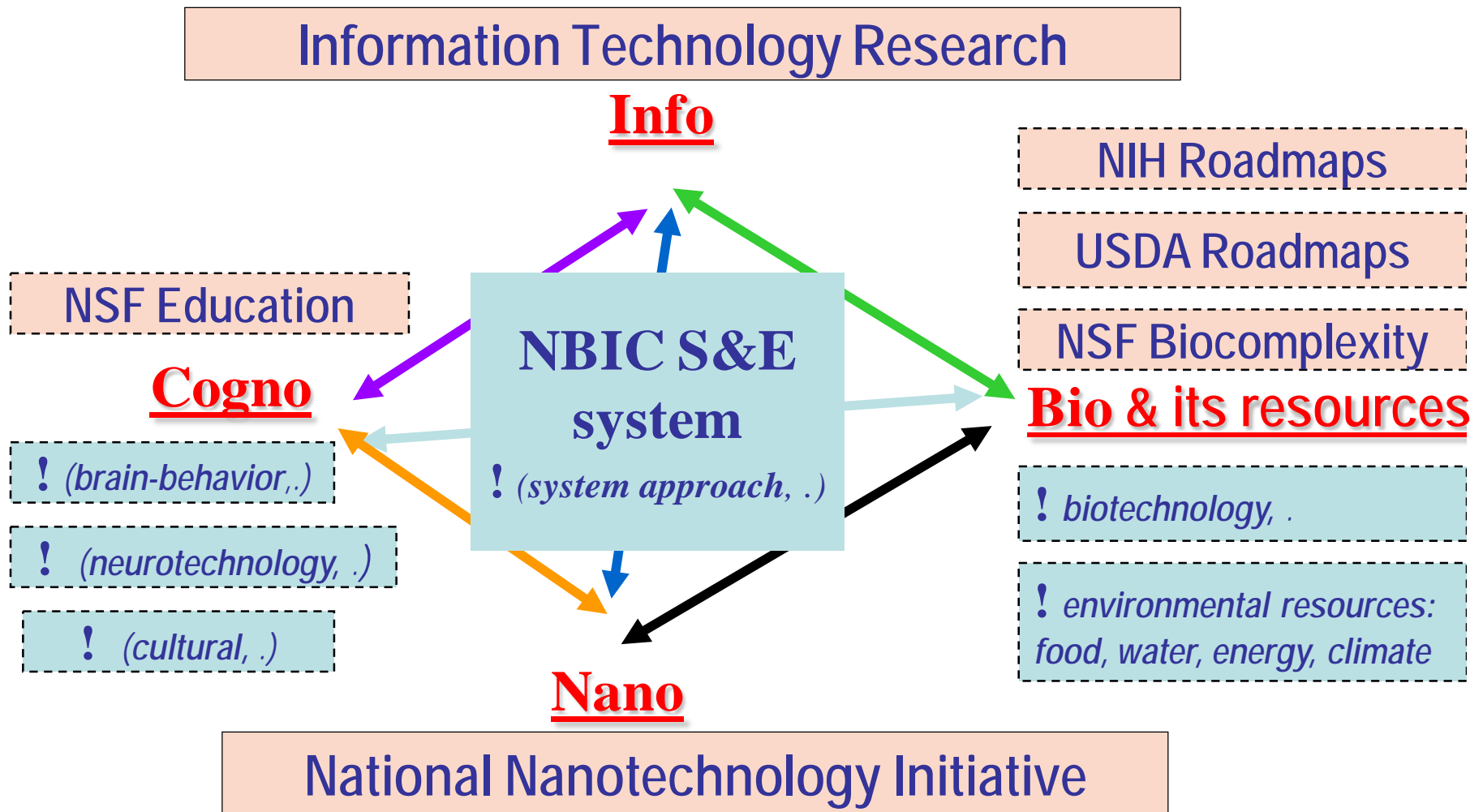
Context: Emergence of new technologies

- Knowledge generation quasi-exponential growth
- Societal needs of radically new technologies
- Emerging technologies governance is essential.
Human potential and technological development are coevolving with benefits and risks:
Prometheus giving the fire: "An eternity of torture"
- Technology implications are global issues:
human development, E-W & N-S balance, safety..

Converging New Technologies transforming tools

("push"/ "pull" balance in U.S. 2000 - 2010)

	R&D		Broad Use
IT	1960	-	2000
BIO	1980	-	2010
NANO	2000	-	2020
NBIC	2010	-	2030



Five studies on convergence

2003, 2006 and 2007 Springer; 2004 NYAS;
NSF 2004 (Organizations and Business)




NSF workshop, 2001
www.nsf.gov/nano
In Springer, 2003

MANAGING NANO-BIO-INFO-COGNO
INNOVATIONS

CONVERGING TECHNOLOGIES IN SOCIETY

MIHAIL C. ROCO AND WILLIAM SIMS BAINBRIDGE (Eds.)

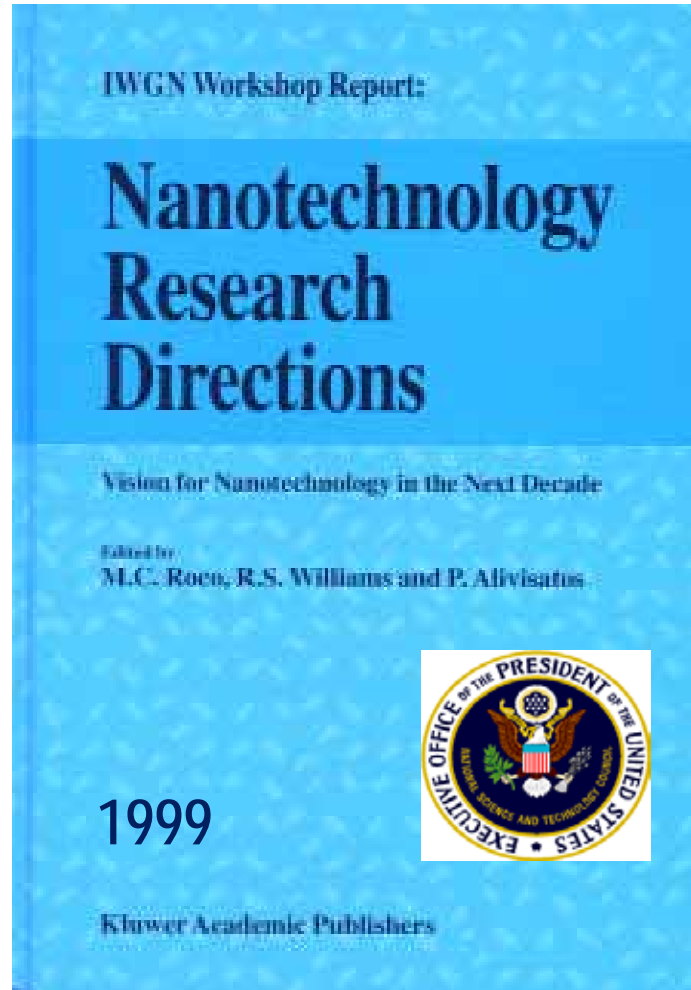


 Springer

November 2006

Long-term nanotechnology research directions (2000-2020)

Nano1 (2000-2010)

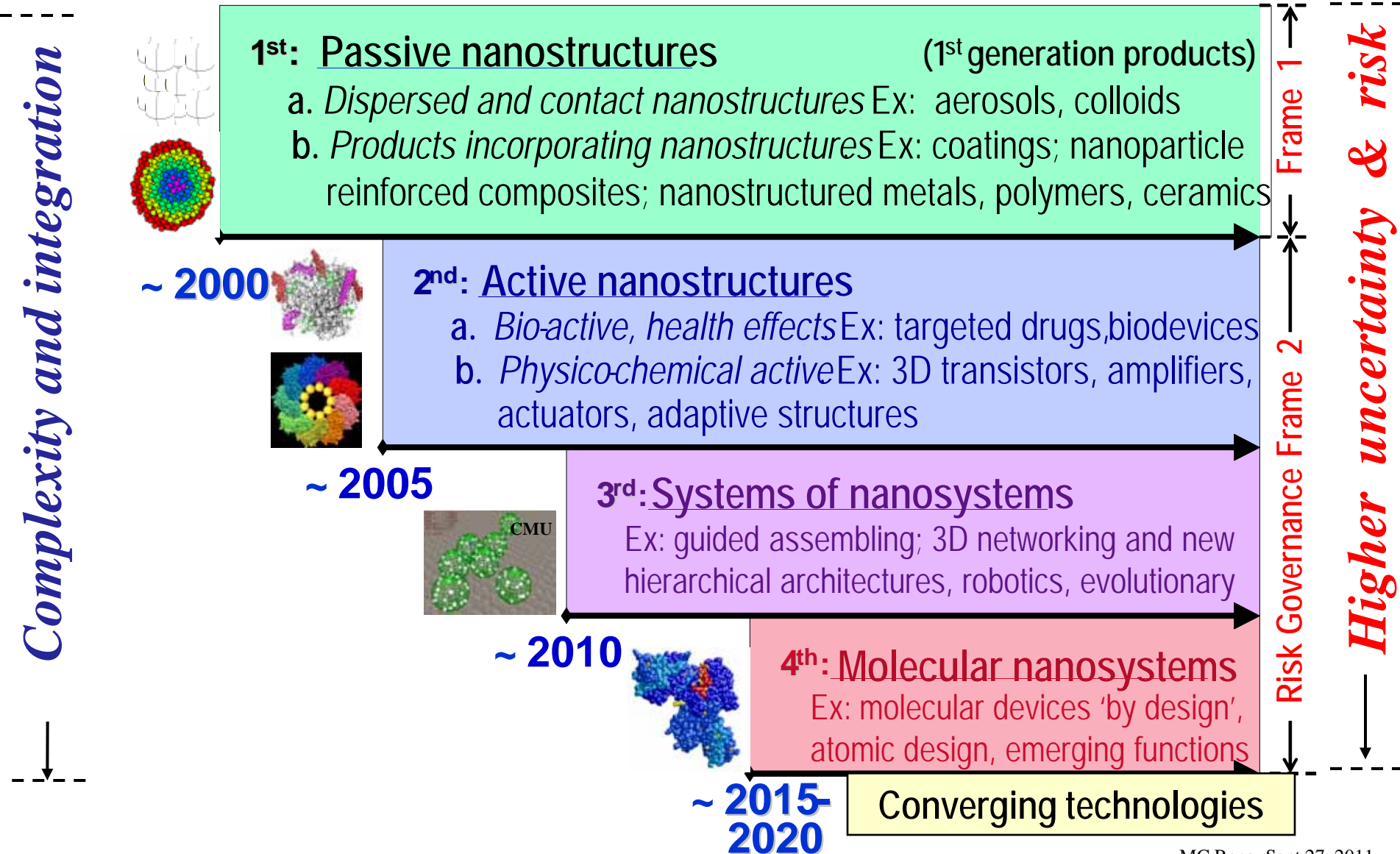


nano2 (2010-2020)



NSF/WTEC, www.wtec.org/nano2/ ; Springer 2010

TIMELINE FOR BEGINNING OF INDUSTRIAL PROTOTYPING AND NANOTECHNOLOGY COMMERCIALISATION: FOUR GENERATIONS OF PRODUCTS AND PRODUCTION PROCESSES



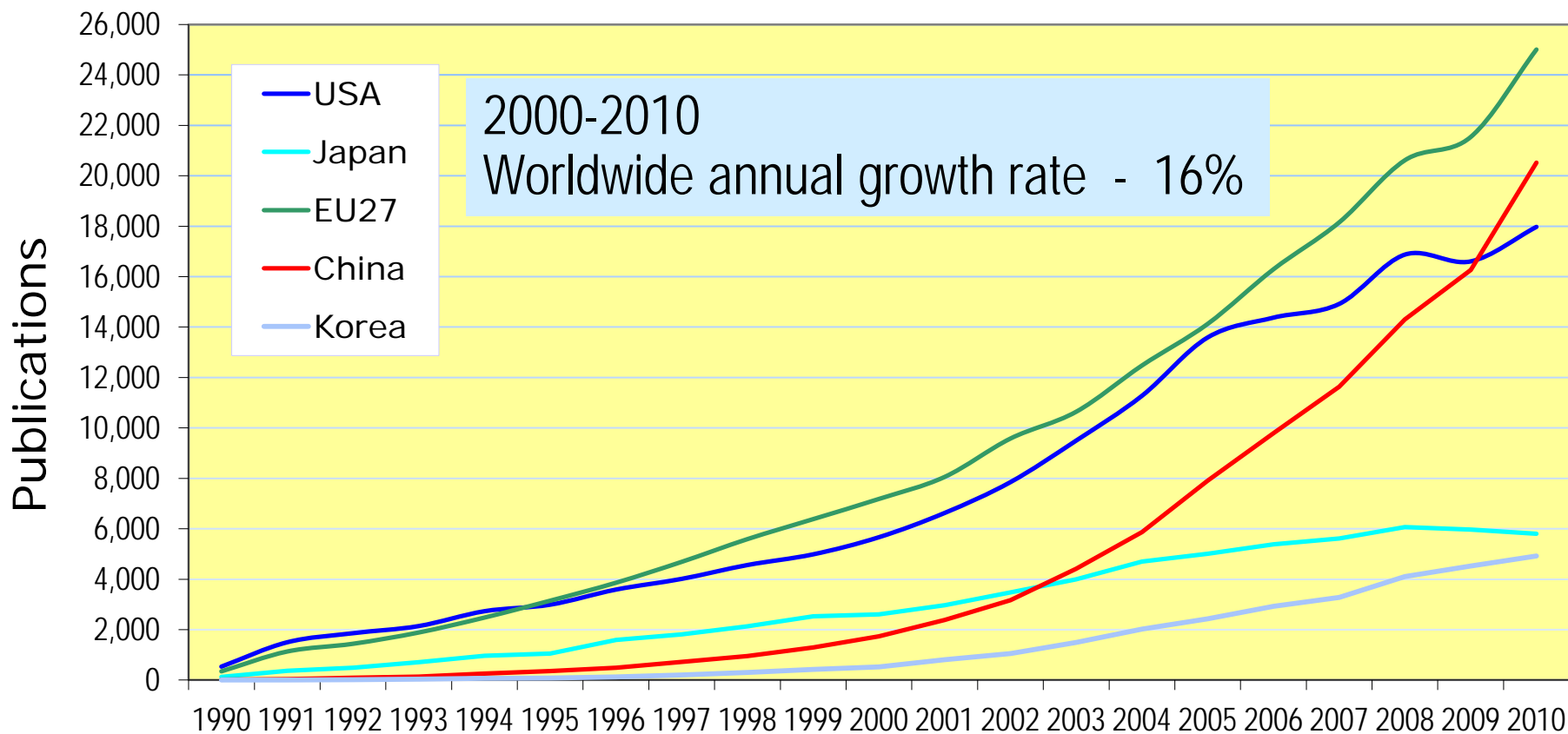
2000-2010

Estimates show an average growth rate of key nanotechnology indicators of 16% - 33%

World (US)	People -primary workforce	SCI papers	Patents applicat- ions	Final Products Market	R&D Funding public + private	Venture Capital
2000 (actual)	~ 60,000 (25,000)	18,085 (5,342)	1,197 (405)	~ \$30 B (\$13 B)	~ \$1.2 B (\$0.37 B)	~ \$0.21 B (\$0.17 B)
2010 (actual)	~ 600,000 (220,000)	78,842 (17,978)	~ 20,000 (5,000)	~ \$300 B (\$110 B)	~ \$18 B (\$4.1 B)	~ \$1.3 B (\$1.0 B)
2000 - 2010 average growth	~ 25% (~23%)	~ 16% (~13%)	~ 33% (~28%)	~ 25% (~24%)	~ 31% (~27%)	~ 30% (~35%)
2015 (estimation in 2000)	~ 2,000,000 (800,000)			~ \$1,000B (\$400B)		
2020 (extrapolation)	~ 6,000,000 (2,000,000)			~ \$3,000B (\$1,000B)		
Evolving Topics	Research frontiers change from <u>passive nanostructures in 2000-2005</u> , to <u>active nanostructures after 2006</u> , and to <u>nanosystems after 2010</u>					

Nanotechnology publications in the Science Citation Index (SCI) 1990 - 2010

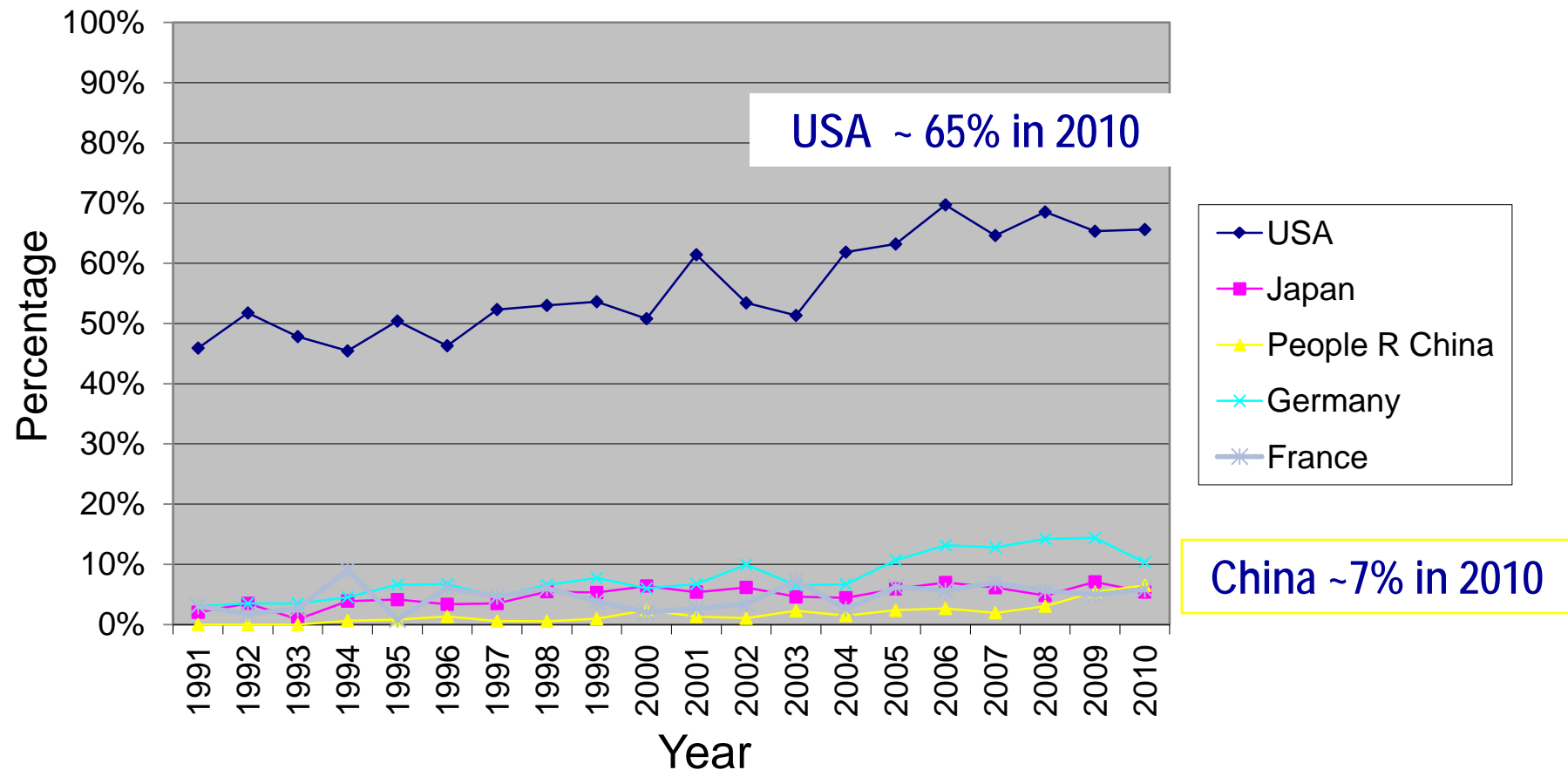
Data was generated from online search in Web of Science using "Title-abstract" search in SCI database for nanotechnology by keywords (Chen and Roco, 2011)



Rapid, uneven growth per countries

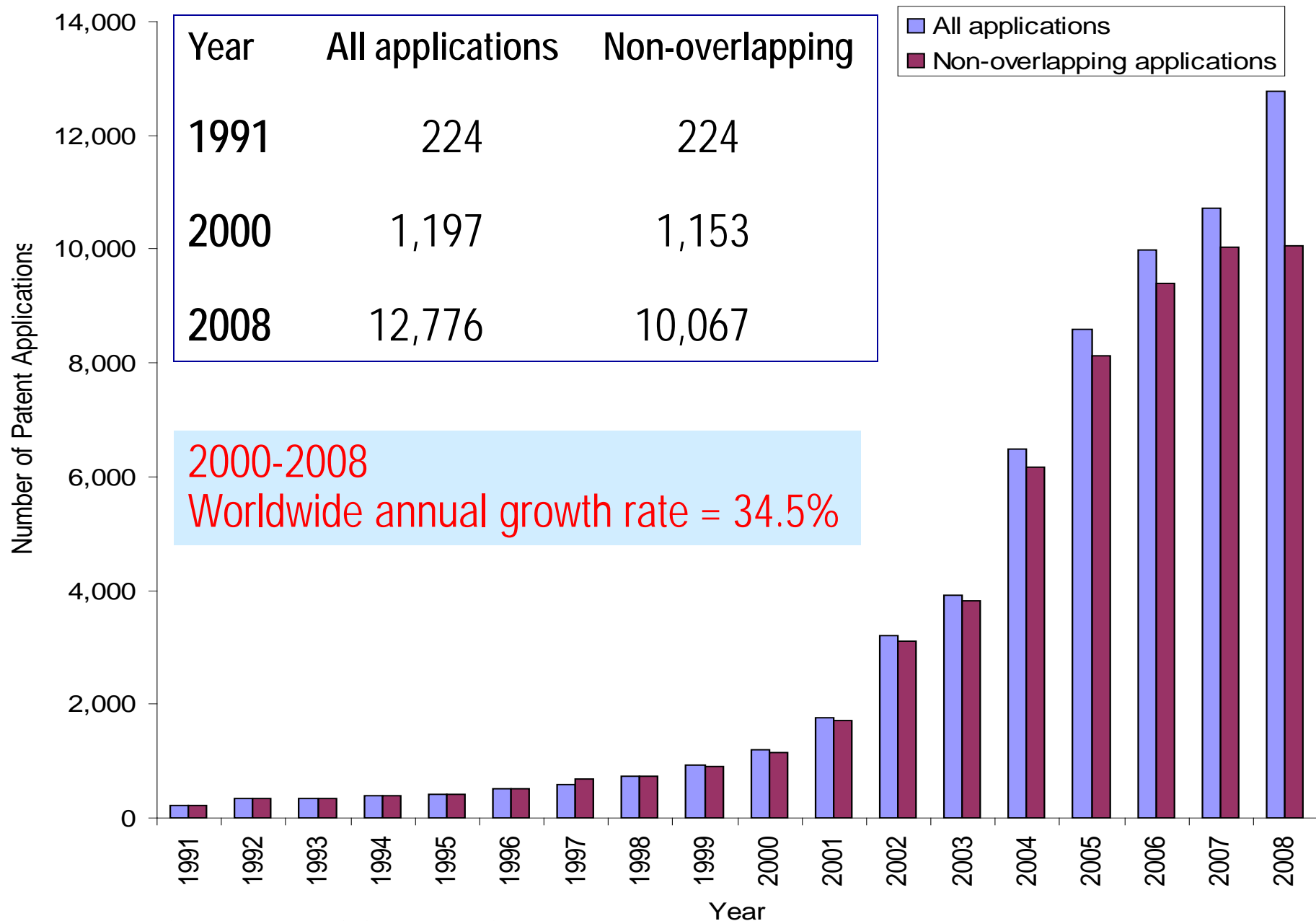
Percent contribution by country to nanotechnology publications in Science, Nature, and Proc. NAS

Title-abstract search (Chen and Roco, 2011)



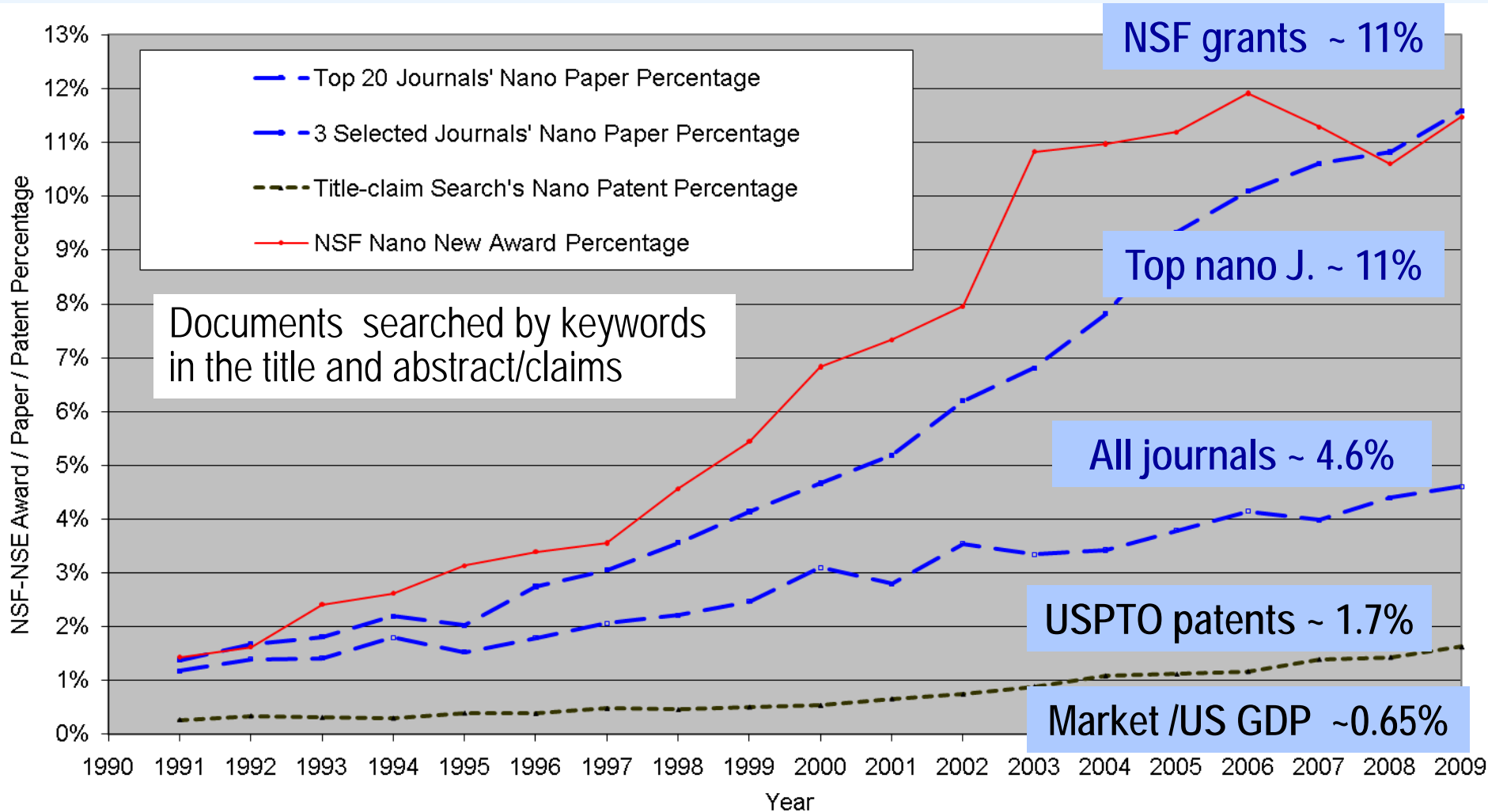
U.S. maintain the lead in highly cited publications

WORDWIDE NUMBER OF NANOTECHNOLOGY PATENT APPLICATIONS



Percentage of nanotechnology content in NSF awards, ISO papers and USPTO patents (1991-2009)

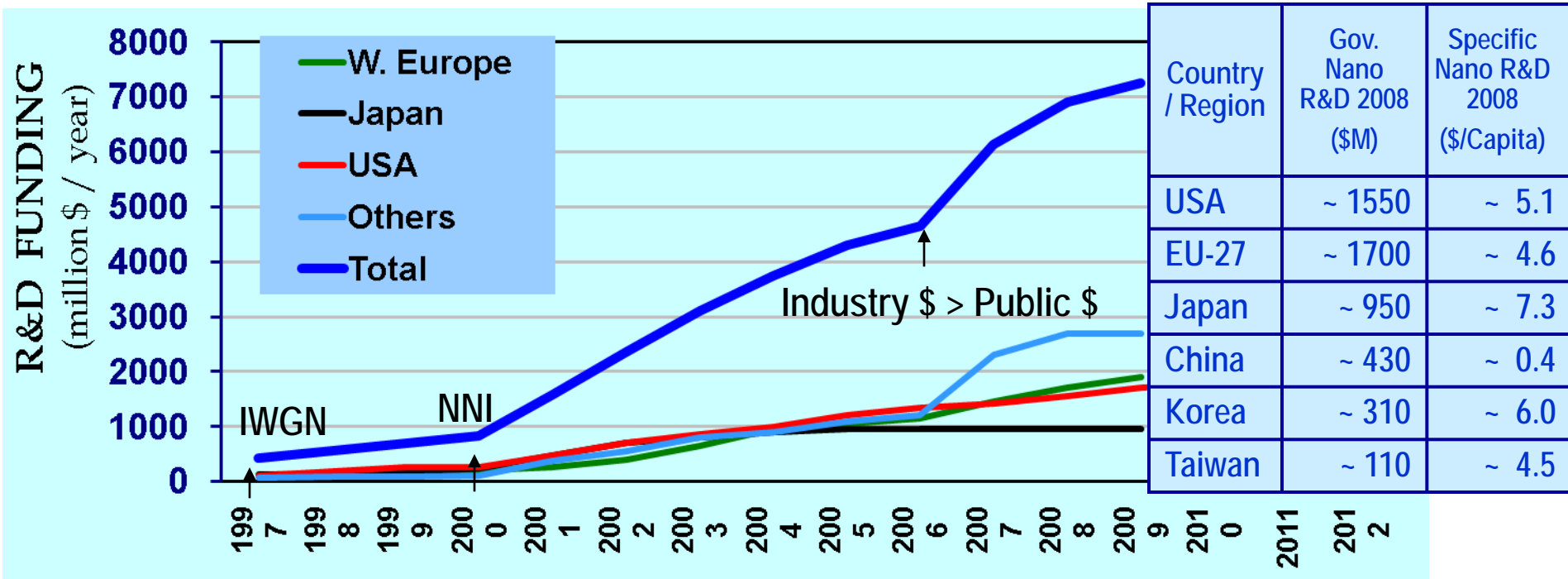
(update after Encyclopedia Nanoscience, Roco, 2008)



Similar, delayed penetration curves: for R&D funding /papers /patents /products /ELSI

2000-2009

Changing international context: federal/national government R&D funding (NNI definition)



Seed funding
1991 - 1997

NNI Preparation
vision/benchmark

1st Generation products
passive nanostructures

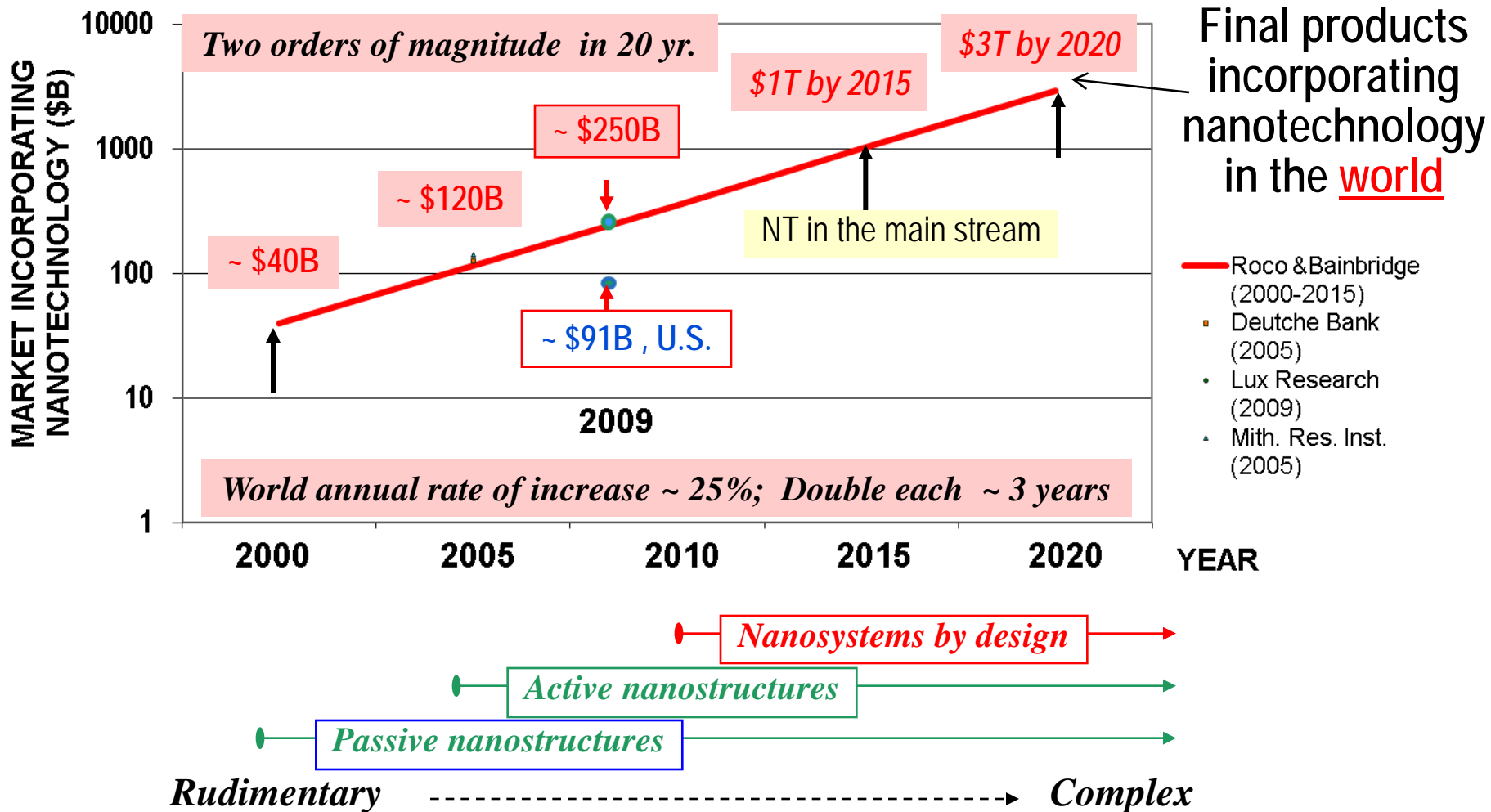
2nd Generation
active nanostructures

3rd Generation
nanosystems

Rapid, uneven growth per countries

WORLDWIDE MARKET INCORPORATING NANOTECHNOLOGY

(Estimation made in 2000 after international study in > 20 countries)



Reference: Roco and Bainbridge, Springer, 2001

2000-2010 Outcomes

- Remarkable scientific discoveries than span better understanding of the smallest living structures, uncovering the behaviors and functions of matter at the nanoscale, and creating a library of 1D - 4D nanostructured **building blocks for devices and systems**
- New S&E fields have emerged such as: *spintronics, plasmonics, metamaterials, carbon nanoelectronics, molecules by design, nanobiomedicine, branches of nanomanufacturing, and nanosystems*
- Technological breakthroughs in advanced materials, biomedicine, catalysis, electronics, and pharmaceuticals; **expansion into** energy resources and water filtration, agriculture and forestry; and **integration of nanotechnology with other emerging areas** such as quantum information systems, neuromorphic engineering, and synthetic and system nanobiology

2001-2010

RE ~10,900
awards

by NSF's
Principal
Investigators

(patents
searched by
"title-claims"
keywords
at USPTO;
examples)

Interval	2001-2010	NSF supported investigators with most patents - NNI at 10 years -	
Rank	Name NSF P.I.	Institution	# USPTO Patents (keyword search)
1	Chad A. Mirkin	Northwestern University	74
2	Richard E. Smalley	Rice University	70
3	Bin Yu	University of Albany	55
4	Stephen R. Quake	Stanford University	48
5	Mark E. Thompson	University of Southern California	43
6	Moungi G. Bawendi	Massachusetts Institute of Technology	42
7	Andrew G. Rinzler	University of Florida	40
8	Ping Liu	University of Texas at Arlington	37
9	Joseph M. Jacobson	Massachusetts Institute of Technology	36
10	George M. Whitesides	Harvard University	33
11	Axel Scherer	California Institute of Technology	31
12	Thomas J. Pinnavaia	Michigan State University	26
13	Tobin J. Marks	Northwestern University	23
14	Charles M. Lieber	Harvard University	23
15	Nathan S. Lewis	California Institute of Technology	22
16	Hongjie Dai	Stanford University	22
17	Kerry J. Vahala	California Institute of Technology	20
18	Thomas W. Kenny	Stanford University	20
19	Michael N. Kozicki	Arizona State University	19
20	Tsu-Jae King	University of California at Berkely	19
21	Robert Langer	Massachusetts Institute of Technology	18
22	Michael L. Simpson	University of Tennessee	18
23	Michael L. Roukes	California Institute of Technology	17
24	Jackie Y. Ying	Massachusetts Institute of Technology	17
25	Ting Guo	University of California at Davis	16
26	Stephen C. Minne	Stanford University	15
27	Nicholas L. Abbott	University of Wisconsin-Madison	15
28	Eric V. Anslyn	Univerisit of Texas at Austin	14
29	R. Stanley Williams	HP	14
30	Kenneth J. Klabunde	Kansas State University	14
31	Samuel I. Stupp	Northwestern University	14

BRIC (country group) and China – largest growth rates in the last decade

- **“Nanotechnology Research Directions for Societal Needs in 2020”** (Roco, Mirkin and Hersam), 2010 (BRIC and China in the global context)
- **“Trends for Nanotechnology Development in China, Russia and India ”** (Liu et al.), J. Nanoparticle Research, 2009, 1845-1866 (trends for papers and patents)
- **“Investor Status and Knowledge Diffusion in Nanotechnology: China, Russia and India”** (Liu et al.)J. of Am. Soc. for Information S&T, 2011, 1166-1176 (trends for innovation and networking)
- China’s nano papers amount to **15% of its published research output** (Small, M. Grieneisen and M. Zhang, 2011)

Ten highly promising products incorporating nanotechnology in 2010

- Catalysts
- Transistors and memory devices
- Structural applications (coatings, hard materials, cmp)
- Biomedical applications (detection, implants,..)
- Treating cancer and chronic diseases
- Energy storage (batteries), conversion and utilization
- Water filtration
- Video displays
- Optical lithography and other nanopatterning methods
- Environmental applications

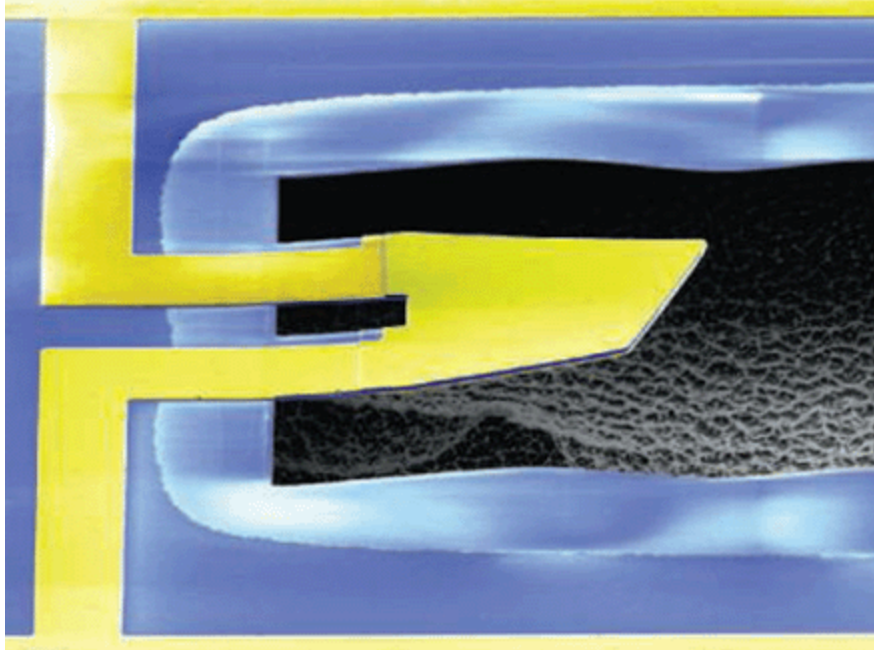
With safety concerns: cosmetics, food, disinfectants,..

2010 nanosystems: nano-radio, tissue eng., fluidics, etc



The First Quantum Machine

Science 17 December 2010: vol. 330 no. 6011 1604



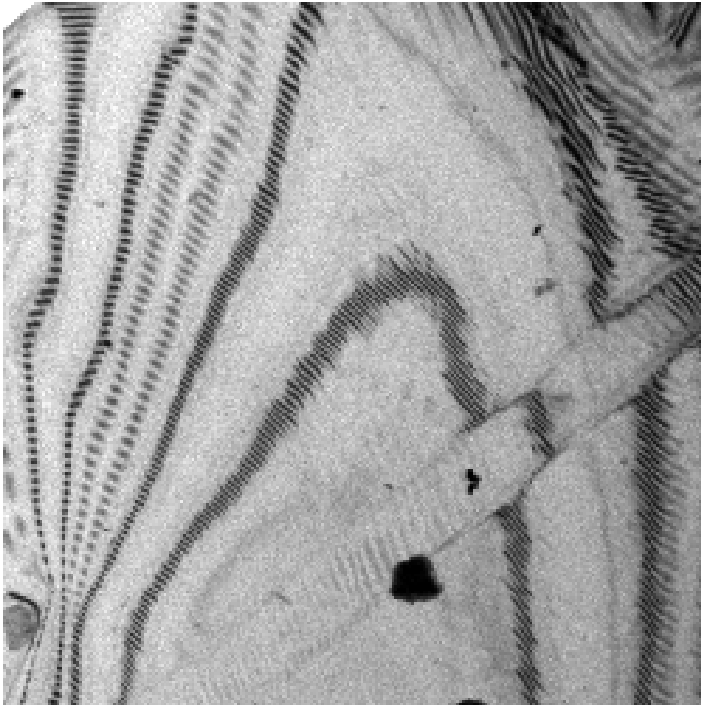
The simplest quantum states of motion with a vibrating device was measured (the board of aluminum is as long as a hair is wide)

Aaron O'Connell and Andrew Cleland, UCSB, 2010



4D Microscope Revolutionizes the Way We Look at the Nano World

A. Zewail, Caltech, and winner of the 1999 Nobel Prize in Chemistry



Nanodrumming of graphite,
visualized with 4D microscopy.

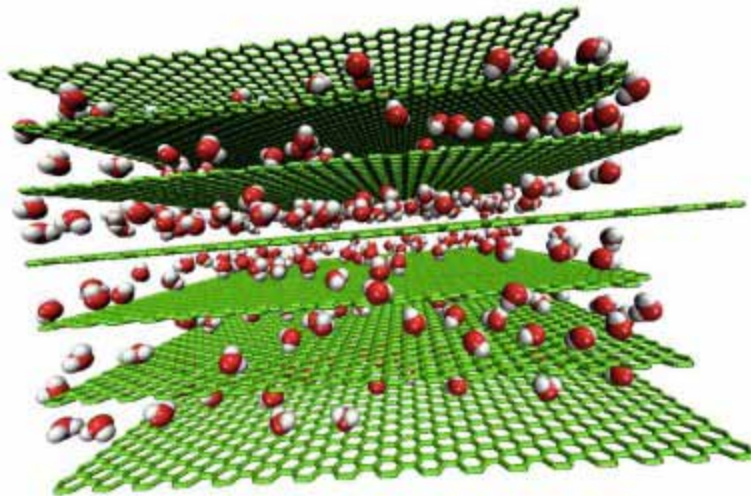
http://ust.caltech.edu/movie_gallery/

Use of ultra short laser flashes to observe fundamental motion and chemical reactions in real-time (timescale of a femtosecond, 10^{-15} s), with 3D real-space atomic resolution.

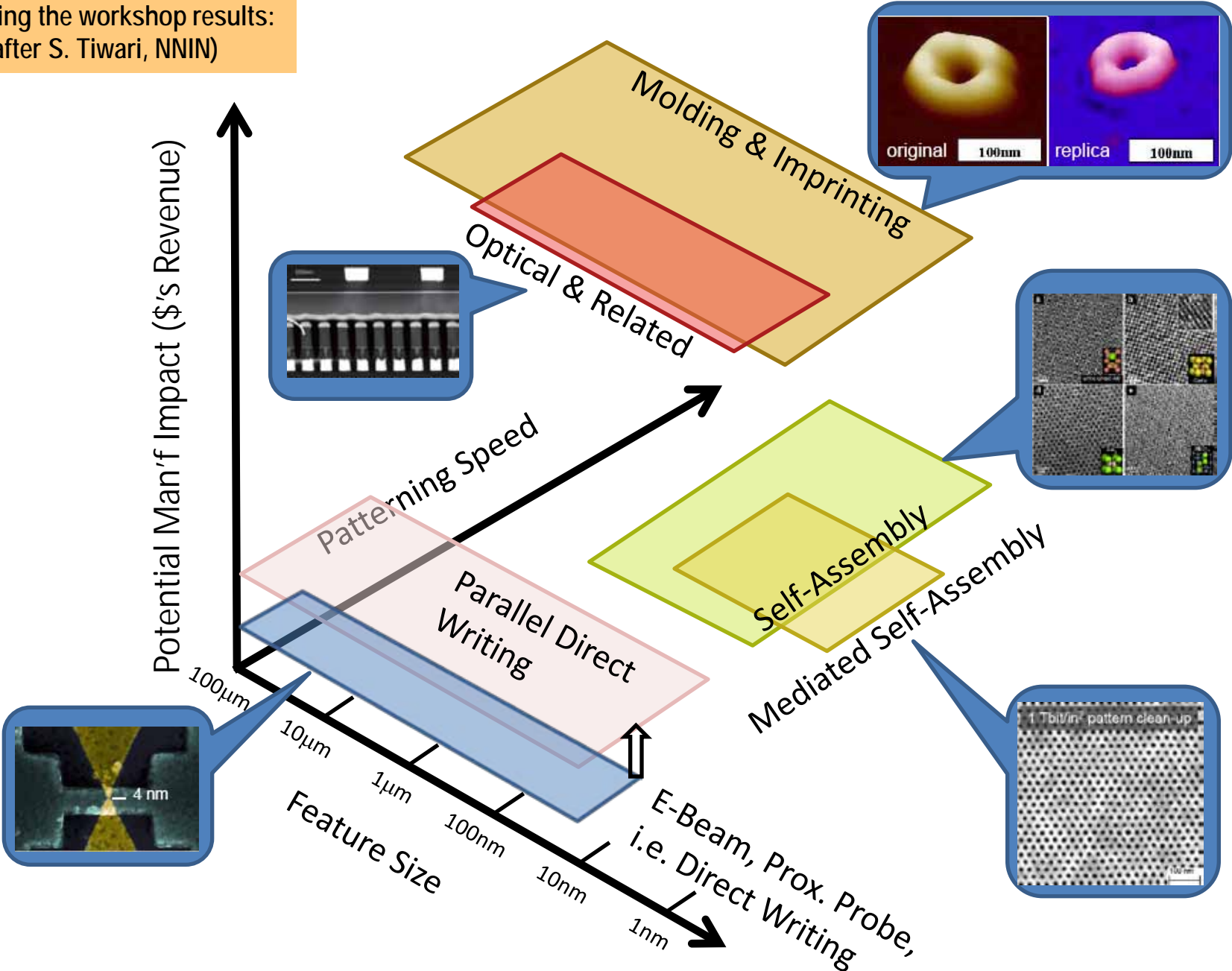
Allows for visualization of complex structural changes (dynamics, chemical reactions) in real space and real time. Such visualization may lead to fundamentally new ways of thinking about matter

Graphite + water = the future of energy storage (Monash U., July 2011)

Keeping graphene moist – in gel form – provides repulsive forces between the sheets and prevents re-stacking, making it ready for energy storage applications

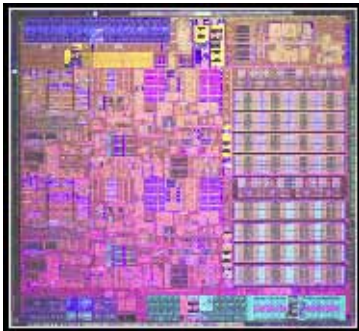


Model for reporting the workshop results:
synthetic view (after S. Tiwari, NNIN)

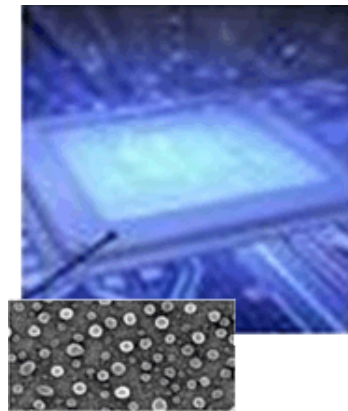


Nanopatterning on surfaces

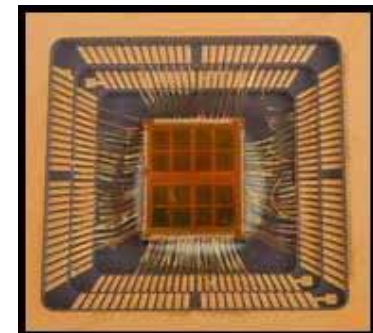
Nanoelectronic and nanomagnetic components incorporated into common computing and communication devices, in production in 2010



32 nm CMOS processor technology by Intel (2009)



90 nm thin-film storage (TFS) flash flexmemory by Freescale (2010)



16 megabit magnetic random access memory (MRAM) by Everspin (2010)

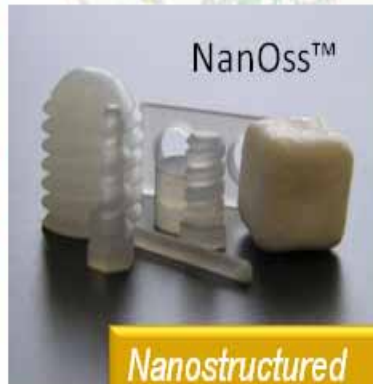
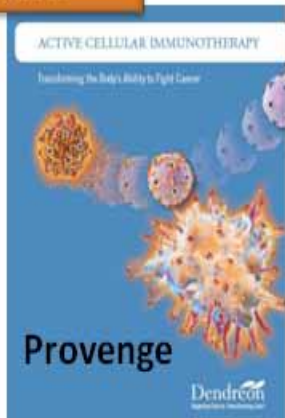
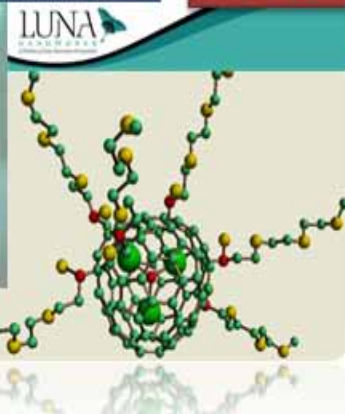
On-site diagnostics



*Nanoscale body
Imaging*



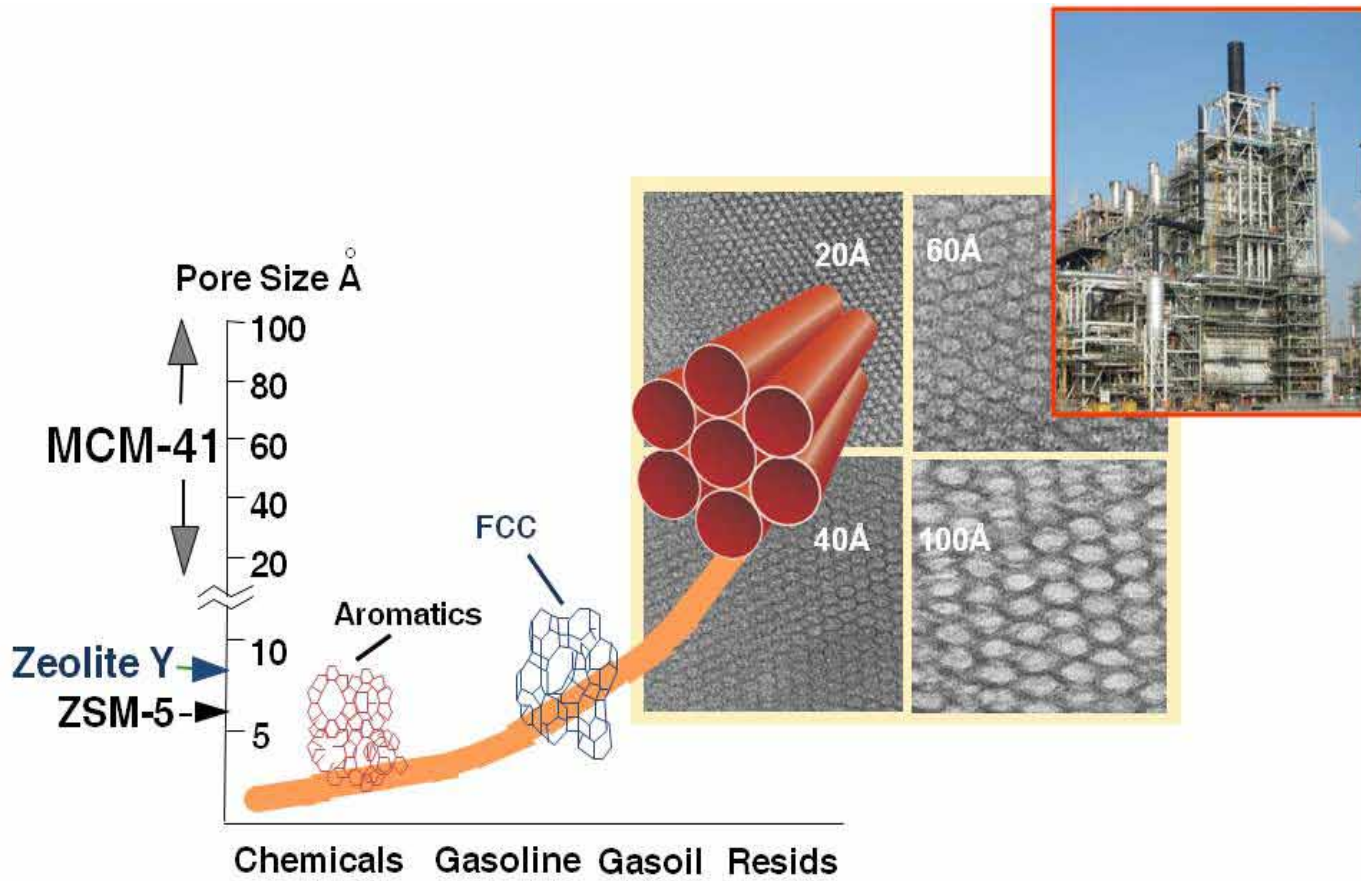
*Targeted drug
therapeutics*



*Nanostructured
bone replacements*

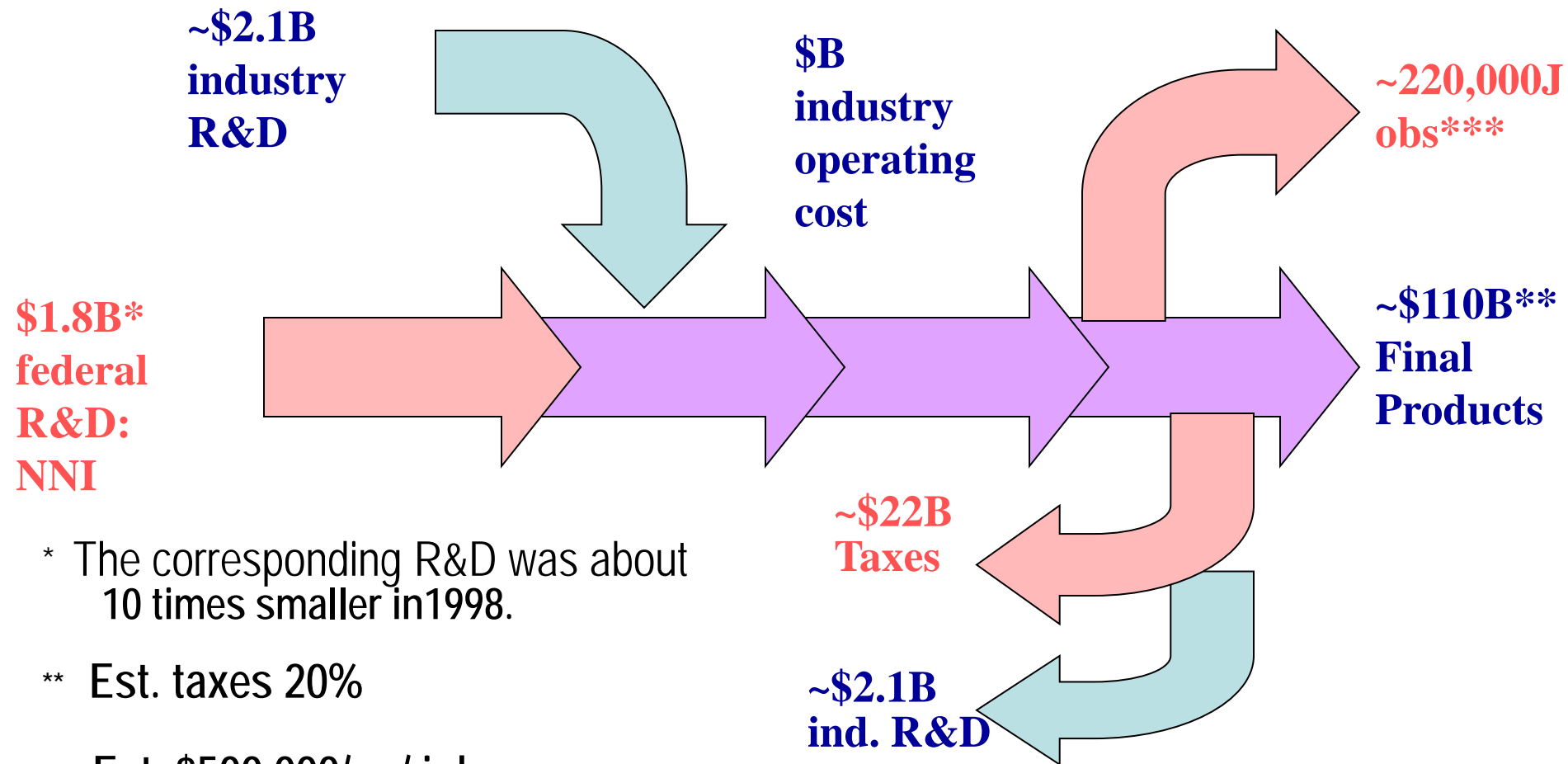
Examples of nanotechnology
incorporated into commercial
healthcare products,
in production in 2010

Examples of nanotechnology in commercial catalysis products for applications in oil refining, in production in 2010



Redesigned since 2000 mesoporous silica materials, like MCM-41, along with improved zeolites, are used in a variety of processes such as fluid catalytic cracking (FCC) for producing gasoline from heavy gas oils, and for producing polyesters. Nano-engineered materials now constitute 30–40% of the global catalyst market

Estimation of Annual Implications of U.S. Federal Investment in Nanotechnology R&D (2010)



* The corresponding R&D was about 10 times smaller in 1998.

** Est. taxes 20%

*** Est. \$500,000/ yr/ job

Examples of Penetration of Nanotechnology in Several Industrial Sectors

The market percentage and its absolute value affected by nanotechnology are shown for 2010

U.S.	2000	2010	Est. in 2020
Semiconductor industry	0 (with features < 100 nm) 0 (new nanoscale behavior)	60% (~\$90B) 30% (~\$45B)	100% 100%
New nanostructured catalysts	0	~ 35% (~35B impact)	~ 50%
Pharmaceuticals (therapeutics and diagnostics)	0	~ 15% (~\$70B)	~ 50%
Wood	0	0	~ 20%

2000-2010: Sustainable Development

- Nanotechnology has provided solutions for about half of the new projects on energy conversion, energy storage, and carbon encapsulation in the last decade
- Entirely new families have been discovered of nanostructured and porous materials with very high surface areas, including metal organic frameworks, covalent organic frameworks, and zeolite imidazolate frameworks, for H storage and CO₂ separations
- A broad range of polymeric and inorganic nanofibers for environmental separations (membrane for water and air filtration) and catalytic treatment have been synthesized
- Testing the promise of nanomanufacturing for sustainability
- Evaluating renewable materials and green fuels

2009 Nanotechnology Regional, State, and Local Initiatives (34)

<http://www.nano.gov/html/funding/businessops.html#RSLI>





NNI increase focus on nanomanufacturing

Ex.: FY 2011 at NSF

- | Nanomanufacturing. The FY 2011 plan includes an increase of about \$10 million to \$32.20 (8% of total NNI budget at NSF)
 - Nanomanufacturing program (2002-) ~ \$9M
 - Signature initiative on scalable nanomanufacturing ~ \$11M (interdisciplinary teams, NIRTs)
 - National Nanomanufacturing Network (2004/2005 -) composed of four Nanoscale Science and Engineering Centers (\$15M, partly from nanomanufacturing program)
 - Single investigator awards , other "core" NSF programs (2001-)
 - IUCRC, GOALI, PFI , SBIR/STTR

Not fully realized objectives after ten years

- ✘ General methods for “**materials by design**” and composite materials (because the direct TMS and measuring techniques methods were not ready)
- ✘ **Sustainable development projects** - only energy projects received significant attention in the last 5 years; Nanotechnology for water filtration and desalination only limited; Delay on nanotechnology for climate research (because of insufficient support from beneficiary stakeholders?)
- ✘ **Widespread public awareness of nanotechnology** – awareness low ~30% in U.S.; Challenge for public participation

Better than expected after ten years

ü Major industry involvement after 2002-2003

Ex: >5,400 companies with papers/patents or products (US, 2008); **NBA** in 2002; Keeping the **Moore law** continue 10 years after serious doubt raised in 2000

ü Unanticipated discoveries and advances in several S&E fields: plasmonics, metamaterials, spintronics, graphene, cancer detection and treatment, drug delivery, synthetic biology, neuromorphic engineering, quantum information ..

ü The formation / strength of the international community, including in nanotechnology EHS and ELSI that continue to grow

Nanotechnology Governance

NANOTECHNOLOGY GOVERNANCE

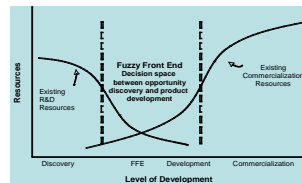
- Investment policy
- Science policy
- Risk management
- Others

Four key functions:

Visionary

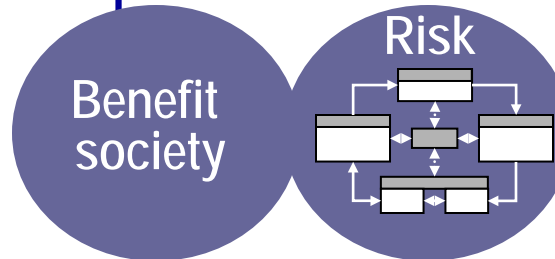
1999: Outline 2000-2020
Nano1: Vision 2000-2010
Nano2: Vision 2010-2020

Transformative



Invest in tools, infrastructure
Education, Innovation
Short and long term results

Responsible



Risk
Governance
(EHS, ELSI,..)

Inclusive

Disciplines, Economy
sectors,
Agencies,
International

Planning NNI “signature initiatives” with nanomanufacturing components in FY 2012

Sustainable Nanomanufacturing

\$ 84M (NSF \$35.4M; DOE \$35.3M; NIST \$7.4M; NASA \$5M; USDA/FS \$0.9M)

Nanoelectronics for 2020 and Beyond

\$ 98.5M (NSF \$50M, DOE \$33.8M; NIST \$11.7M; NASA \$3M)

Nanotechnology for Solar Energy

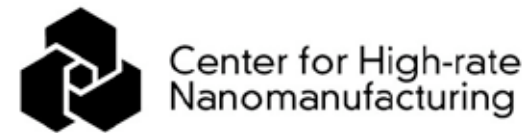
\$ 125.7M (DOE \$79.2M; NSF \$32M; NIST \$11.5M; NASA \$2M; USDA/NIFA \$1M)



National Nanomanufacturing Network (2006-)

Its core: Four Nanomanufacturing NSECs

- Center for Hierarchical Manufacturing (CHM)
 - U. Mass Amherst/UPR/MHC/Binghamton
- Center for High-Rate Nanomanufacturing (CHN)
 - Northeastern/U. Mass Lowell/UNH
- Center for Scalable and Integrated Nanomanufacturing (SINAM)
 - UC Berkeley/UCLA/UCSD/Stanford/UNC Charlotte
- Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS)
 - UIUC/CalTech/NC A&T



In FY 2012 Request: a new system oriented nano centers

- **Nanosystems Engineering Research Centers**
for 5 + 5 years (~ \$4 M/year)
- **Pre-proposal in September 2011 ... awards in 2012**
- **Address major topics from discovery to innovation**

**Part of the NNI increased focus on improving the
innovation ecosystem and translational research
in 2011-2012**



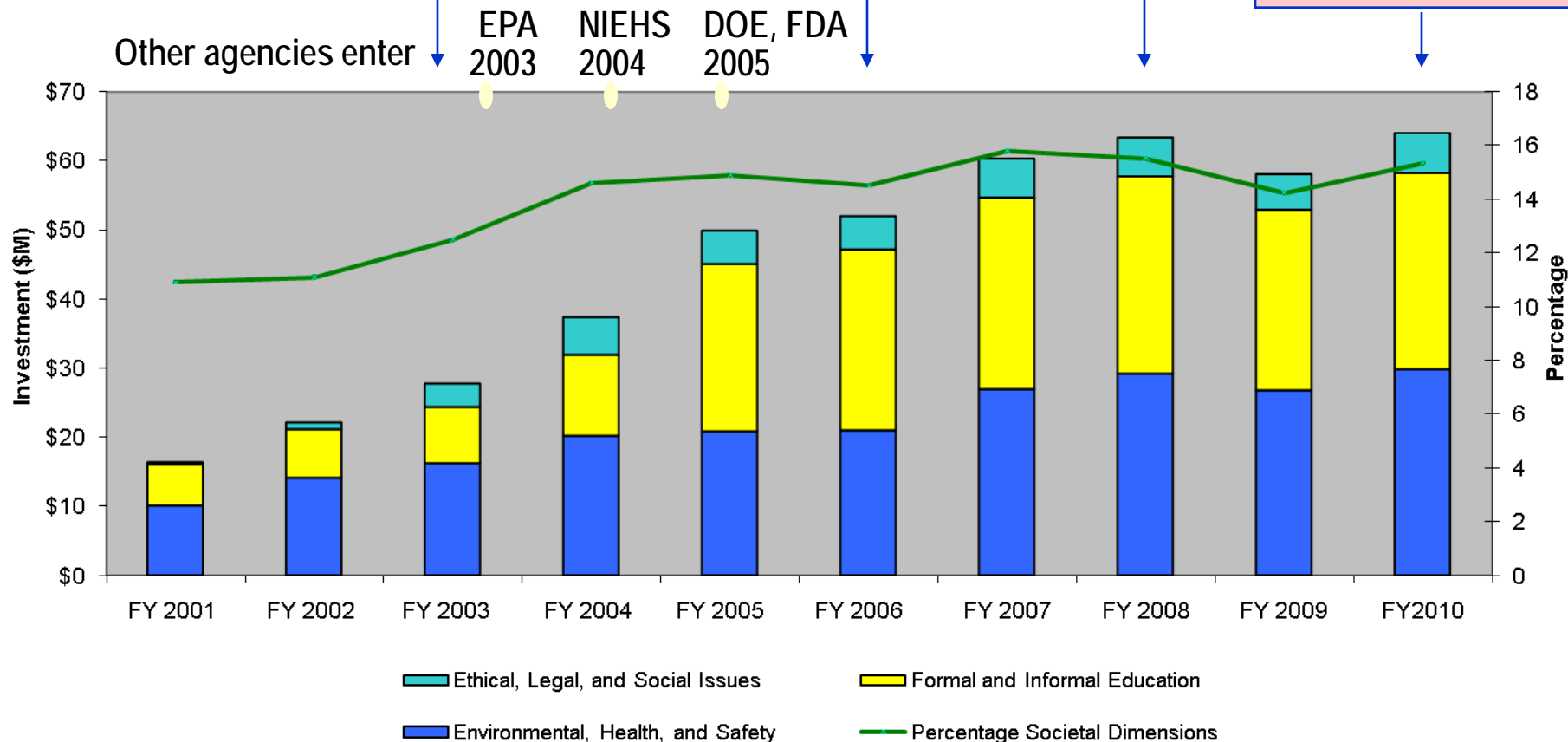
NSF Investment in Nanotechnology Implications for Safety and Society

**Nano-manufacturing
safety added in 2003**

**Focus on future
nano-generations
added in 2006**

**New CEIN
in 2008**

**Focus on
nanosystems
>2010**



Naturally nanostructured materials	Engineered nanostructured materials	Active nanostructures and systems	Large and molecular nanosystems
		Risk Balancing Necessary + Probabilistic Risk Modelling	Risk Trade -off Analysis & Deliberation necessary + Risk Balancing + Probabilistic Risk Modelling
	Probabilistic Risk Modelling	Remedy	Remedy
		• Cognitive • Evaluative	• Cognitive • Evaluative • Normative
	Remedy	Type of Conflict	Type of Conflict
Statistical Risk Analysis	Cognitive	• Agency Staff • External Experts • Stakeholders - Industry - Directly affected groups	• Agency Staff • External Experts • Stakeholders - Industry - Directly affected groups - General public
Remedy	Type of Conflict		
• Agency Staff • External Experts	• Agency Staff • External Experts • Stakeholders		
Actors	Actors	Actors	Actors
Instrumental	Epistemological	Reflective	Participative
Type of Discourse	Type of Discourse	Type of Discourse	Type of Discourse
Simple	Component Complexity induced	System uncertainty induced	Ambiguity induced
Risk Problem	Risk Problem	Risk Problem	Risk Problem

Frame 1

Frame 2

The Risk Management Escalator and Stakeholder Involvement

(from Simple via Complex and Uncertain to Ambiguous Phenomena) with reference to nanotechnology

University-Industry-government partnerships (Public-private hybrids)

- q Nanoelectronics Research Initiative, U.S.
- q U. Albany College of Nanoscale Science and Engineering, U.S.
- q Grenoble center, France
- q IMEC/ Aachen/ Eindhoven triangle
- q University-Industry-Government Tsukuba Nano Center
- q Industrial Technology Research Institute, Taiwan



University-Industry Demonstration Partnerships (Academies, U.S.).

Ex: TurboNegotiator (www.turbo.sitesetup.net) a software tool that would facilitate the negotiation of industry-university research agreements

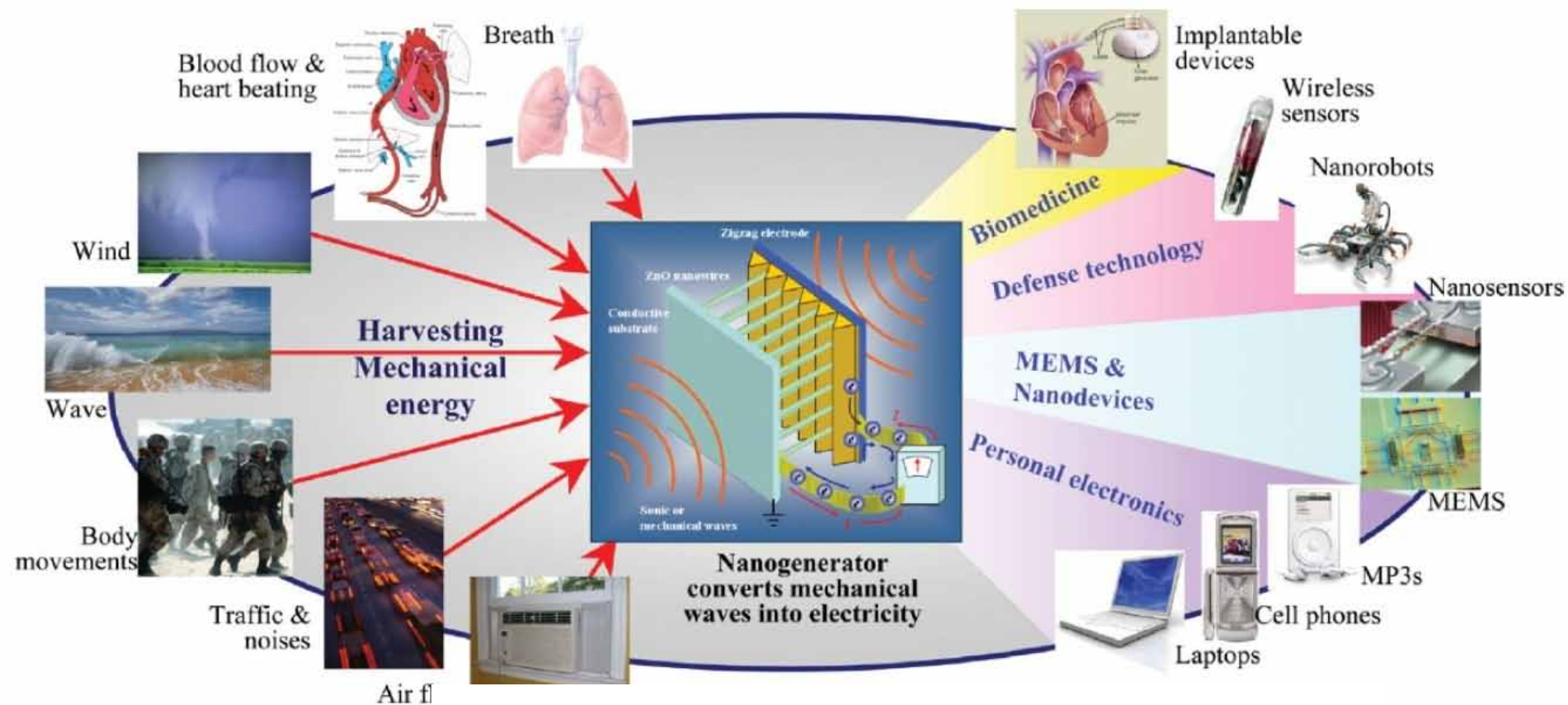
Twelve trends to 2020

www.wtec.org/nano2/

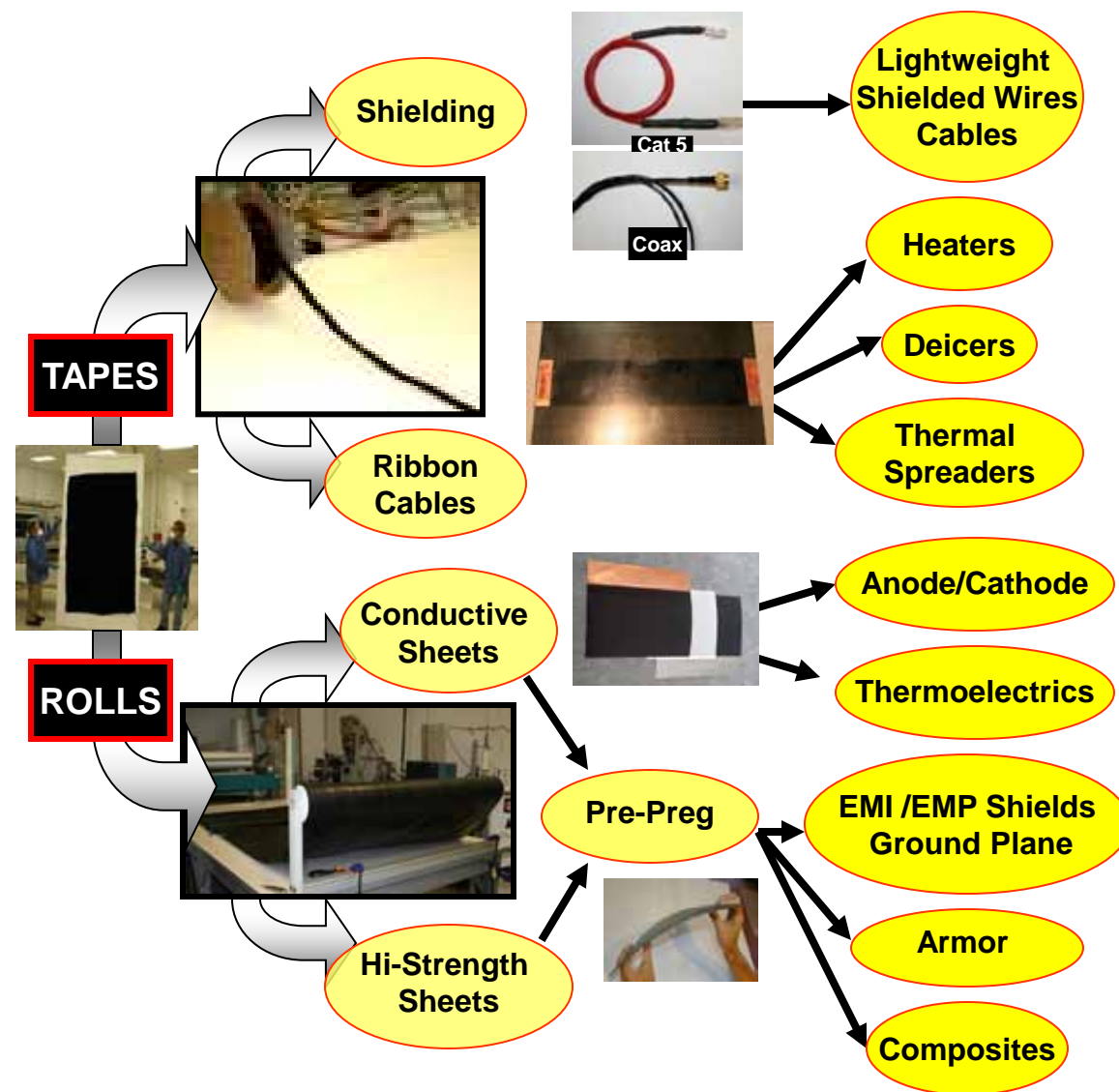
- Theory, modeling & simulation: x1000 faster, essential design
- “Direct” measurements – x6000 brighter, accelerate R&D & use
- A shift from “passive” to “active” nanostructures/nanosystems
- Nanosystems, some self powered, self repairing, dynamic
- Penetration of nanotechnology in industry - toward mass use; catalysts, electronics; innovation– platforms, consortia
- Nano-EHS – more predictive, integrated with nanobio & env.
- Personalized nanomedicine - from monitoring to treatment
- Photonics, electronics, magnetics – new capabilities, integrated
- Energy photosynthesis, storage use – solar economic by 2015
- Enabling and integrating with new areas – bio, info, cognition
- Earlier preparing nanotechnology workers – system integration
- Governance of nano for societal benefit - institutionalization

Ex: Self-powered nanosystems

Multifunctional, self-powered nanosystems (using fluid motion, temperature gradient, mechanical energy..) in wireless devices, biomedical systems...



Expanded CNT sheet production with broad impact



Commercial and Defense Impact Multi-Industry Use





NSF (2001-): Converging technologies (NBIC) - Examples of new transdisciplinary domains

- **Quantum information science** (IT; Nano and subatomic physics; System approach for dynamic/ probabilistic processes, entanglement and measurement)
- **Eco-bio-complexity** (Bio; Nano; System approach for understanding how macroscopic ecological patterns and processes are maintained based on molecular mechanisms, evolutionary mechanisms; interface between ecology and economics; epidemiological dynamics)
- **Neuromorphic engineering** (Nano, Bio, IT, neurosc.)
- **Cyber-physical systems** (IT, NT, BIO, others)
- **Synthetic & system biology** (Bio, Nano, IT, neuroscience)
- **Cognitive enhancers** (Bio, Nano, neuroscience)

Vision for the next ten years

- § Preparing for **mass application of nanotechnology by 2020**, with shift to more complex generations of nanotechnology products and increased connection to biology. Risk governance deficits in knowledge, uncertainty, institutional
- § **Greater emphasis on innovation and commercialization:** incentives for greater use of public/private partnerships to foster innovation. Create new models for innovation
- § **Focus on job creation and return to society** - high-added value nanomanufacturing
- § *Nanotechnology governance will be **institutionalized** , with increased globalization and a co-funding mechanism*

Several background references

- "Nanotechnology Research Directions", Springer 2000
- "Societal Implications of Nanoscience and Nanotechnology", Springer (2001); updated in 2 volumes in 2007
- "International strategy for nanotechnology research and development", Journal of Nanoparticle Research 3, 353–360 2001
- "The NNI: Past, Present and Future", in Handbook on Nanoscience, Engineering and Technology, CRC, Taylor and Francis 2007
- "Nanotechnology Risk Governance" in Global Risk Governance Framework, Springer 2007
- "Possibilities for Global Governance of Converging Technologies", J. Nanoparticle Res. 2008
- "Mapping Nanotechnology Innovations and Knowledge" Springer 2009
- "Nanotechnology Research Directions for Societal Needs in 2020" Springer (Roco, Mirkin and Hersam 2010)